

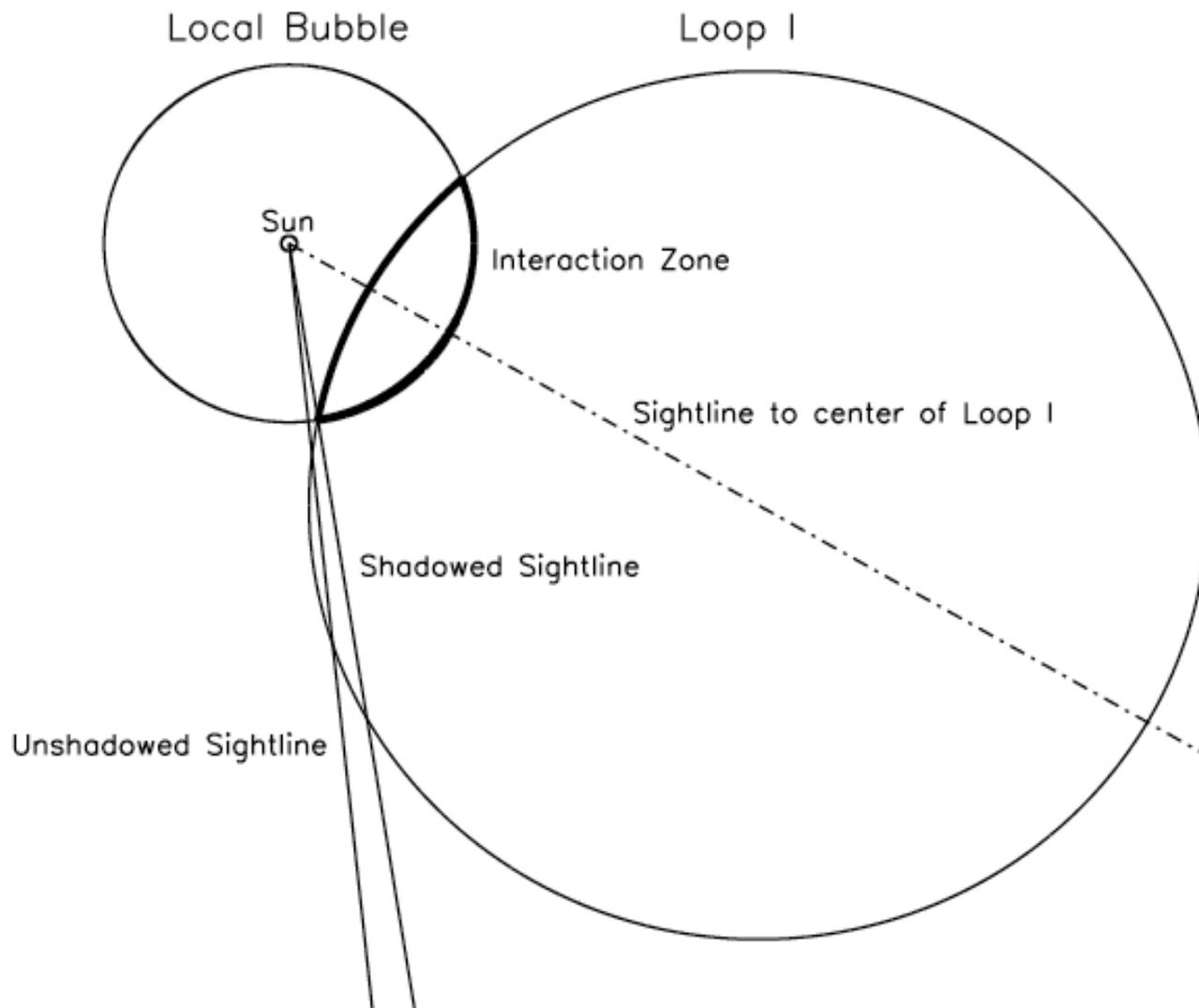
***FUSE* Observations of the Loop I / Local Bubble Interaction Region**

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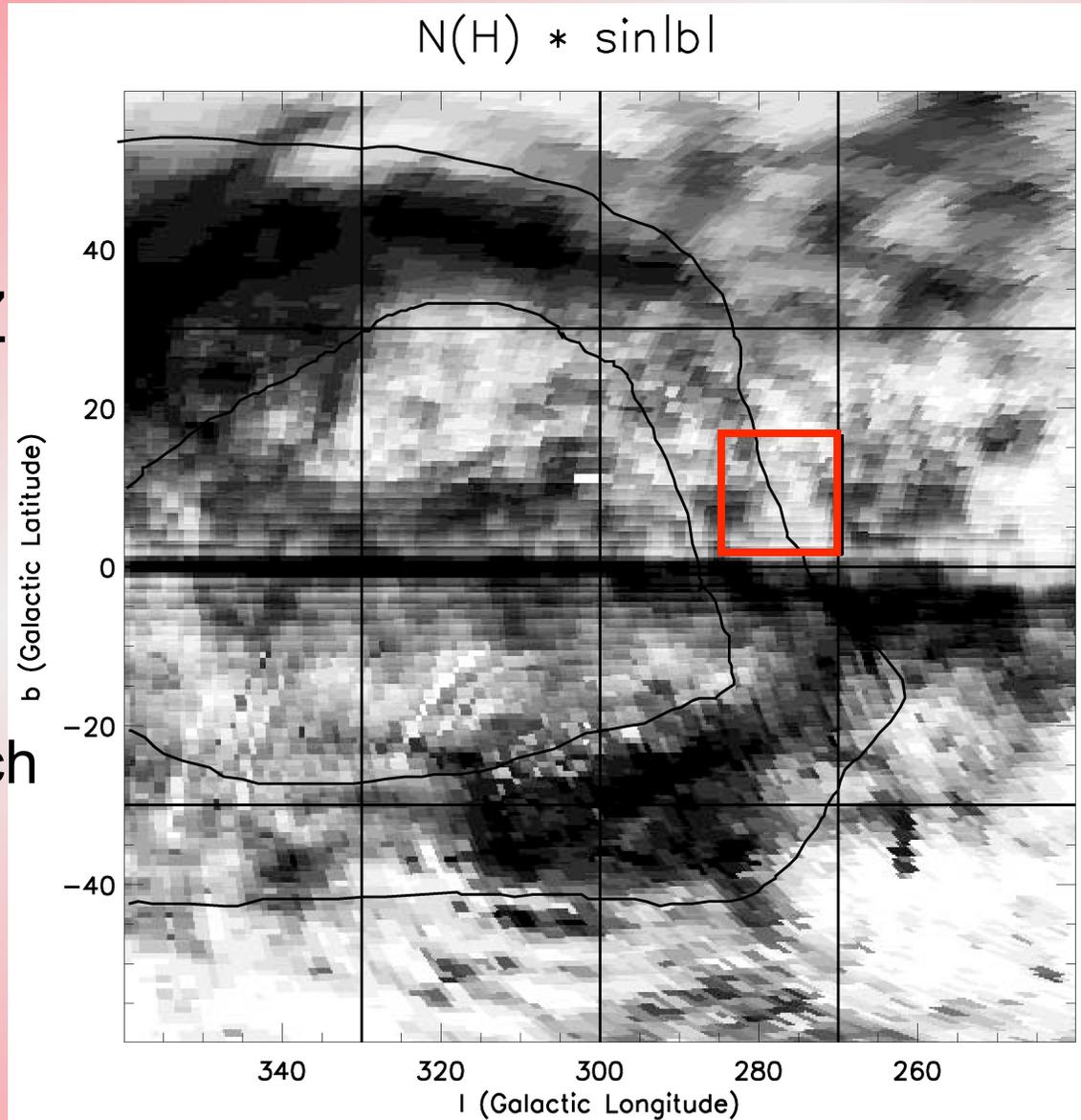
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Schematic Orientation



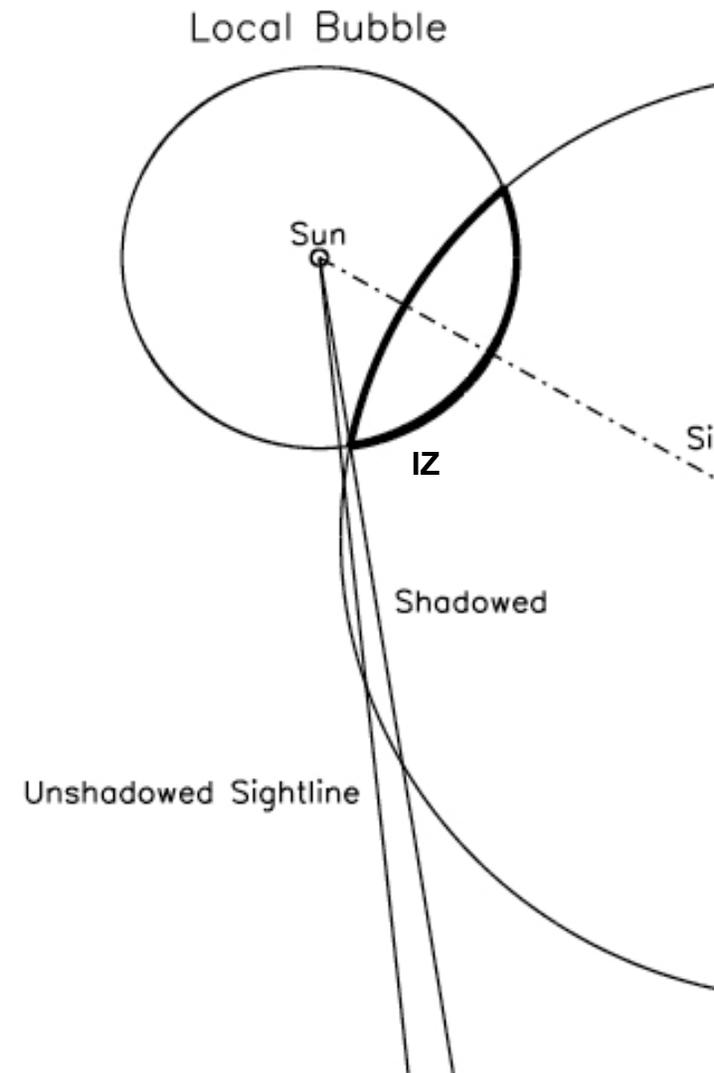
Interaction Zone

- Neutral H map of IZ
 - Dickey & Lockman (1990)
- IZ annulus
 - Egger & Aschenbach (1995)



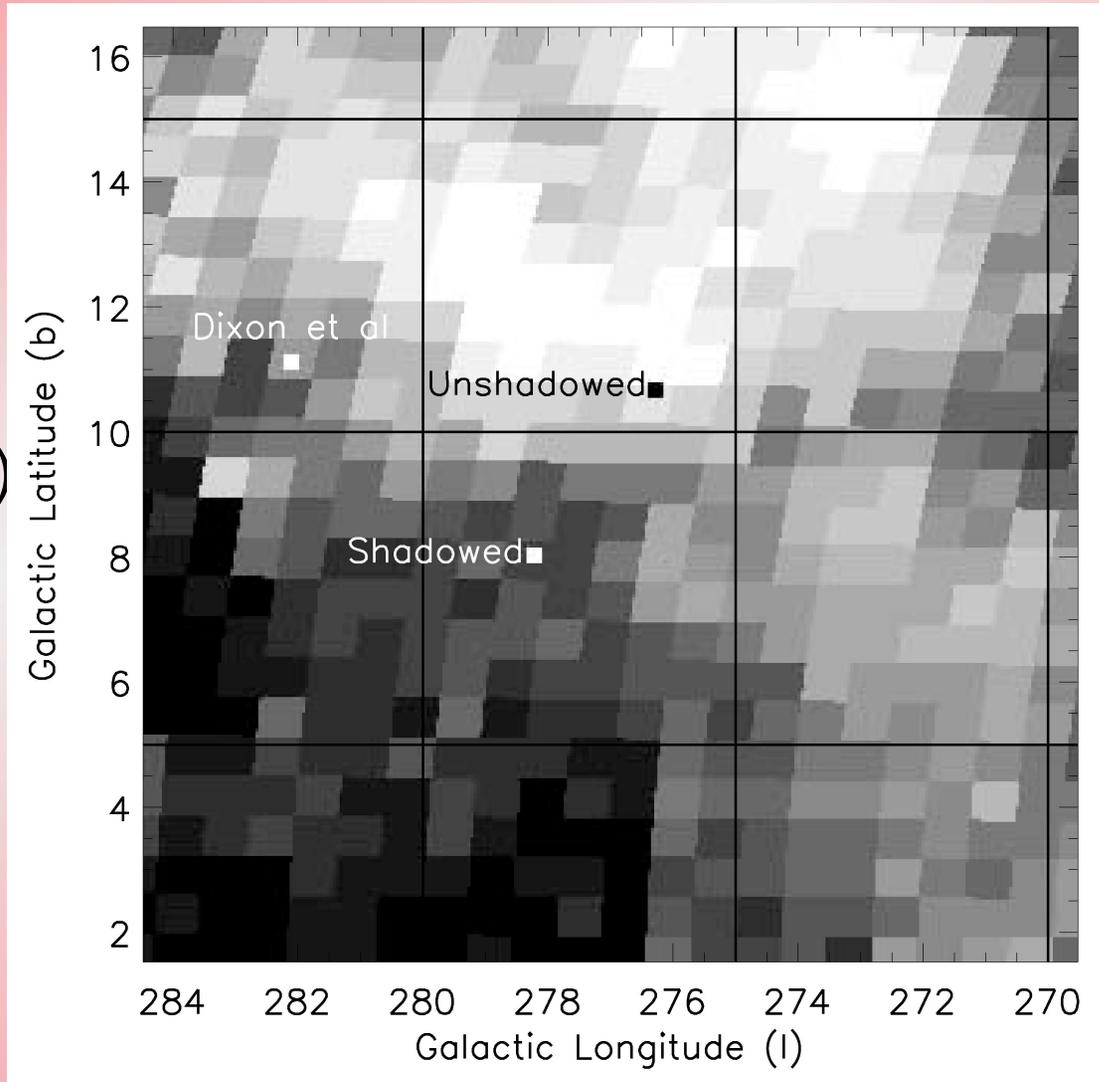
Shadowing Strategy

- Compare OVI (O^{5+}) emission along two adjacent sightlines along edge of IZ
 - “Shadowed” goes through IZ
 - “Unshadowed” goes outside IZ
- Compared with “Unshadowed” sightline, “Shadowed” sightline
 - has low RASS $\frac{1}{4}$ keV emission
 - has higher $N(HI)$
 - distant OVI should be blocked



X-ray Shadowing

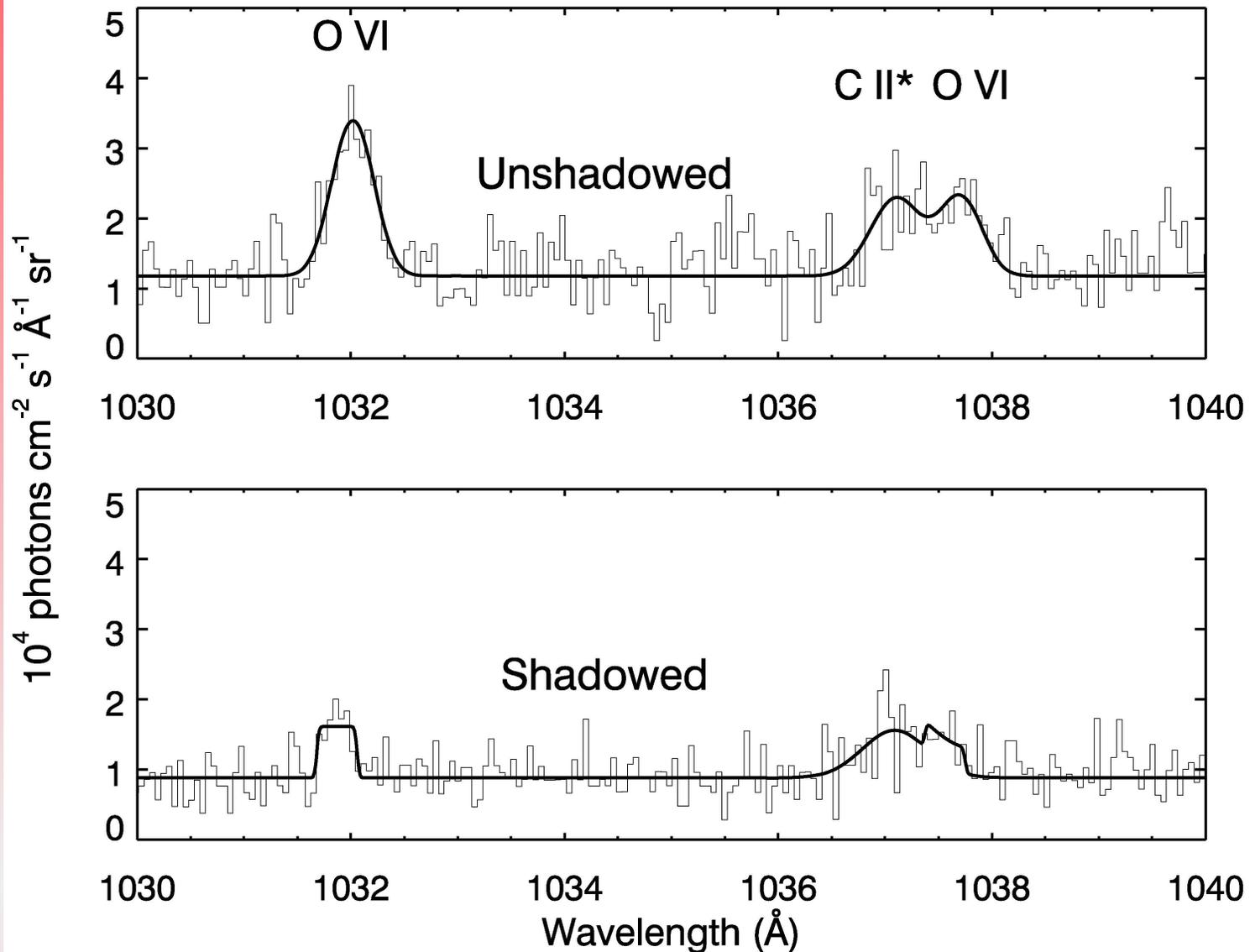
- RASS $\frac{1}{4}$ keV map near our pointings
 - Snowden et al. (1997)



FUSE data

- “Unshadowed”: $(l, b) = (276.26^\circ, +10.692^\circ)$
 - 2004 April 3 / 4,
 - 43 ksec total, 30 ksec orbital night
- “Shadowed”: $(l, b) = (278.23^\circ, +8.02^\circ)$
 - 2002 June 27-29, 2003 Feb 18 / 19
 - 60 ksec total, 40.6 ksec orbital night
- Only consider data from orbital night
- Emission lines:
 - Modeled as 106 km/s tophat convolved with Gaussian
 - Gaussian contains instrumental contribution of ~ 25 km/s (Dixon et al. 2006)

OVI emission spectra



Emission Intensities

Species	Wavelength (Å)	Shadowed Intensity (LU)	Unshadowed Intensity (LU)
O VI	1031.93	2750 ± 550	10800 ± 1200
C III	977.02	13300 ± 2200	15000 ± 5000

Comparison with other Superbubble measurements

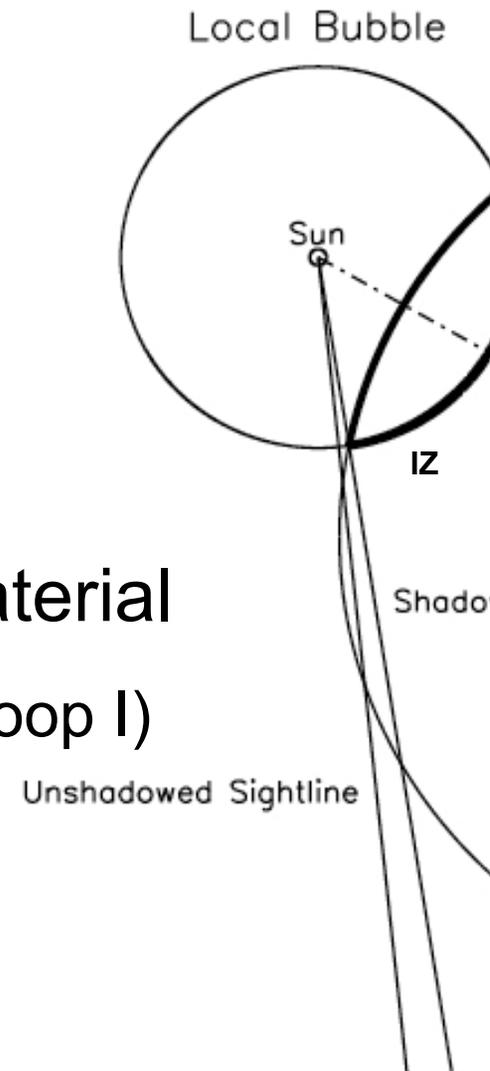
- *FUSE*: Dixon et al. 2006 survey
 - $I_{\text{OVI}} > 8000$ LU for 2 sightlines (Monogem Ring, Outskirts of Vela / Gum Nebula)
- *SPEAR*:
 - $I_{\text{OIV}} \sim 180\,000$ LU towards much younger Vela (Nishikida et al. 2006)
 - $I_{\text{OVI}} \sim 7000$ LU along edge of Orion-Eridanus Superbubble (Kregenow et al. 2006)
 - Confined to region $\sim 5\text{-}10$ pc across

Modeling Physical Conditions

$$I_{\text{shadowed}} = I_{LB} + I_{\text{beyond}} e^{-\tau_s}$$

$$I_{\text{unshadowed}} = I_{LB} + I_{\text{beyond}} e^{-\tau_{us}}$$

- Expect IZ to contain most absorbing material
 - τ_{us} may be non-zero (boundaries of LB & Loop I)
 - For now, set $\tau_{us} = 0$ & $\tau_s = \tau_{IZ}$



OVI Emission Within Loop I

$$I_{\text{shadowed}} = I_{LB} + I_{\text{beyond}} e^{-\tau_{IZ}}$$

$$I_{\text{unshadowed}} = I_{LB} + I_{\text{beyond}}$$

- Assumptions:
 - I_{LB} & I_{beyond} are the same along both sightlines
 - Difference in optical depth between sightlines (τ_{IZ}) is entirely due to material in the IZ

CASE I: IZ Completely Opaque

- $\tau_s = \tau_{IZ} = \infty$

- $I_{LB} = 2750 \pm 550$ LU

- $I_{beyond} = 8050 \pm 1320$ LU

- Unlikely to be correct!

- Gives lower limit on OVI interior to Loop I

- ***Substantial OVI emission arises beyond the IZ***

CASE II: Shadowed sightline has average IZ properties

- $N(H I) = 7 \times 10^{20} \text{ cm}^{-2}$ (Egger & Aschenbach 1995)

$$\tau_{IZ} = 2.3 \quad (\text{Sasseen et al. 2002})$$

$$\rightarrow I_{LB} = 1890 \pm 620 \text{ LU}$$

$$I_{beyond} = 8910 \pm 1460 \text{ LU}$$

- I_{LB} inconsistent with Shelton (2003) upper limit

- ***More OVI emission arising in interfaces on near side of IZ than elsewhere in LB***

OR

- ***Neutral H in this direction is less than average (Case III)***

CASE III: No Local Emission

- $I_{LB} = 0 \text{ LU}$

- $I_{beyond} = 10800 \pm 1200 \text{ LU}$

- $\tau_{IZ} = 1.4 \pm 0.2$

- $N(H I) = (4.1 \pm 0.7) \times 10^{20} \text{ cm}^{-2}$

(Sasseen et al. 2002)

- Gives **lower limit** on neutral H column density of IZ
- $N(H I)$ less than this gives unphysical (–ve) Local Bubble Emission
- No significant change if use Shelton (2003) upper limit $I_{LB} = 600 \text{ LU}$

- ***This is our preferred scenario***

IZ Column Density

- Egger & Aschenbach (1995):
 - Avg. $N(\text{HI}) \sim 7 \times 10^{20} \text{ cm}^{-2}$
 - Too much local OVI emission
- Reis & Corradi (2007):
 - $N(\text{HI})$ near our sightlines $\sim 2 \times 10^{20} \text{ cm}^{-2}$
 - $2 \times$ smaller than lower limit consistent with our assumptions
 - Our “Shadowed” sightline chosen due to notable X-ray shadow, so could easily be higher

Physical Conditions Inside Loop I

- Model parameters:
 - Input: *ROSAT* count rates (R_{12} and R_{34}) along both sightlines
 - *CHIANTI* equilibrium plasma model
 - Assume T_{plasma} & X-ray emission measure same on both sightlines
 - Output spectrum absorbed along:
 - “Unshadowed” sightline by a non-IZ neutral H column (τ_{us})
 - “Shadowed” sightline by that + additional IZ contribution ($\tau_s = \tau_{IZ} + \tau_{us}$)
- Results:
 - $T = 1.26 \pm 0.06$ million K
 - Non-IZ column density = $(1.5 \pm 0.2) \times 10^{20} \text{ cm}^{-2}$
 - IZ column density = $(4.0 \pm 0.2) \times 10^{20} \text{ cm}^{-2}$

(comparable to Case III above)

OVI Emission

- Use these neutral H column densities to determine τ_{us} & τ_s

$$\tau_{us} = 0.50 \pm 0.07 \quad ; \quad \tau_{IZ} = 1.33 \pm 0.07$$

$$\tau_s = \tau_{us} + \tau_{IZ} = 1.83 \pm 0.09$$

$$\rightarrow I_{LB} = -130 \pm 900 \text{ LU}$$

$$I_{beyond} = 18000 \pm 3300 \text{ LU}$$

- ***Consistent with no local emission***

CIII Emission

- Optical Depth to CIII emission 13% higher

$$\rightarrow I_{LB} = 12800 \pm 3400 \text{ LU}$$

$$I_{beyond} = 3800 \quad \begin{array}{l} +12000 \\ -3800 \end{array}$$

- Large errors on distant emission due to opacity of intervening material
- ***Much of the emission arises on the near side of IZ***
 - Substantially more than Shelton (2003) observation within LB
 - Suggests CIII production at inhomogeneous interfaces

Conclusions

- Observed OVI (1032Å) emission:
 - “Shadowed”: $\sim 2750 \pm 550$ LU
 - “Unshadowed”: 10800 ± 1200 LU
- Implications:
 - $\leq \sim 800$ LU arises from near side of IZ
 - OVI emission arising within Loop I: $\sim 10^4$ LU
 - If $n_e \sim 0.1 \text{ cm}^{-3}$, then $l \sim 2.5 \text{ pc}$, $P \sim 30,000 \text{ cm}^{-3} \text{ K}$
- Observed CIII (977Å) similar along both sightlines
 - Much of emission likely arises on near side of IZ

OVI Emission Intensities

TABLE 1
1032 Å O VI EMISSION

Sightline	Data	O VI intensity (LU ^b)	σ_G^c (Å)	FWHM ^c (km s ⁻¹)	V_{LSR} (km s ⁻¹)
Shadowed ^a	Night	2750 ± 550	0.02 ^{+0.03} _{-0.02}	≤ 21 ^d	-29 ± 6
...	Day + Night	2640 ± 600	0.07 ± 0.06	41 ± 41	-29 ± 10
Unshadowed ^a	Night	10800 ± 1200	0.16 ± 0.03	107 ± 21	15 ± 8
...	Day + Night	9580 ± 1000	0.13 ± 0.03	85 ± 21	16 ± 6

^a Shadowed: $(l, b) = (278.23, +8.02)$, Unshadowed: $(l, b) = (276.26, +10.69)$

^b LU = photons cm⁻² s⁻¹ sr⁻¹

^c FWHM have been corrected for instrumental contribution, while σ_G have not. Gas at $T = 3 \times 10^5$ K has a thermal width corresponding to a FWHM of 29 km/s.

^d The best-fit convolving Gaussian has a FWHM less than the instrumental contribution, suggesting the aperture is not filled, although a filled aperture is within the error bars.

TABLE 2
OTHER EMISSION LINES AND UPPER LIMITS

Species	Wavelength (Å)	Detector Segment	SHADOWED			UNSHADOWED		
			Intensity (LU ^b)	σ_G^c (Å)	V_{LSR} (km s ⁻¹)	Intensity (LU)	σ_G^c (Å)	V_{LSR} (km s ⁻¹)
C I ^a	945.58	SiC 2a	2900 ± 1500	...	...	< 8700	...	...
Mg II	946.73	SiC 2a	2500 ± 1000	...	-26 ± 13	<8700	...	...
N I ^a	953.97	SiC 2a	<4400	...	...	<8800	...	...
C III	977.02	SiC 2a	13300 ± 2200	0.14 ± 0.04	-10 ± 10	15000 ± 5000	0.29 ± 0.14	45 ± 35
N III	991.57	SiC 2a	<5300	...	...	<10600	...	...
S III	1015.55	LiF 1a	<1800	...	...	<3200	...	...
C II*	1037.02	LiF 1a	5100 ± 1100	0.28 ± 0.12	8 ± 16	6700 ± 1300	0.21 ± 0.06	13 ± 16
Ar I ^a	1048.22	LiF 1a	5000 ± 1100	0.24 ± 0.07	-61 ± 19	5200 ± 1200	0.17 ± 0.06	-14 ± 16
S IV	1062.66	LiF 1a	1200 ± 800	...	94 ± 45	<3300	...	...
S IV	1072.99	LiF 1a	<2500	...	...	<4000	...	...
N II ^a	1083.99 ^d	SiC 1a	<12000	...	...	20000 ± 6000	...	...
C I ^a	1122.26	LiF 2a	<2300	...	...	<3400	...	...
Fe III	1122.52	LiF 2a	<2300	...	...	3100 ± 1400	...	-17 ± 35
Fe II	1144.94	LiF 2a	2900 ± 800	0.05 ± 0.07	-26 ± 13	2700 ± 1300	0.1 ± 0.1	23 ± 22

^a These lines may contain a contribution due to nighttime airglow

^b LU = photons cm⁻² s⁻¹ sr⁻¹

^c The width of the best-fit convolving Gaussian is not included for lines fit only because they exceeded the 95% confidence limit, as these were poorly determined.

^d Because it was not possible accurately determine the wavelength zero-point of the SiC 1a spectrum, we are unable to determine with certainty which of the NII multiplet lines we observed.

Pathlength

- $I_{\text{OVI}} \rightarrow EM_{\text{OVI}} \sim 0.012 \pm 0.002 \text{ cm}^{-6} \text{ pc}$
- Assume
 - $T \sim 3 \times 10^5 \text{ K}$ for OVI-emitting gas
 - pressure equilibrium (X-ray / OVI)
 - n_e either 0.01 cm^{-3} or 0.1 cm^{-3} (Dixon et al. 2006)
- OVI-emitting pathlength 0.7 to 1.2 times X-ray emitting pathlength
 - OVI pathlength $\sim 120 \text{ pc}$ OR $\sim 1.2 \text{ pc}$
 - Total OVI + X-ray $\sim 250 \text{ pc}$ or $\sim 2.5 \text{ pc}$
- Path through edge of Loop I $\ll 250 \text{ pc}$
 - $n_e \sim 0.1 \text{ cm}^{-3}$
 - $l \sim 2.5 \text{ pc}$
 - $P \sim 30\,000 \text{ cm}^{-3} \text{ K}$

Emission Line Velocities

- “Shadowed”:
 - $V_{\text{LSR}}(\text{OVI}) = -29 \pm 6 \text{ km/s}$
 - $V_{\text{LSR}}(\text{CIII}) = -10 \pm 10 \text{ km/s}$
- “Unshadowed”:
 - $V_{\text{LSR}}(\text{OVI}) = 15 \pm 8 \text{ km/s}$
 - $V_{\text{LSR}}(\text{CIII}) = 45 \pm 35 \text{ km/s}$
- Velocity shift → inhomogeneous properties for gas?
 - Non-uniform surface brightness in aperture could mimic velocity shift (e.g. Shadowed sightline)

Emission Line Widths

- Remove instrumental contribution from convolving Gaussian
 - FWHM < 25km/s → unfilled aperture
 - True for best-fit on Shadowed sightline
- “Shadowed”: upper edge of 1- σ range on convolving Gaussian → $T \sim 2 \times 10^5$ K
- “Unshadowed”: → $T \sim 4$ million K
 - Turbulent broadening?
 - More than one emitting region?